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A comparison of 400 cycle 1000 volt transformers to 60 cycle 450 volt transformers

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A STUDY OF 400 CYCLE TRANSFORMERS

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James Mercer

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A COMPARISON OF 400 CYCLE 1000 VOLT TRANSFORMERS TO 60 CYCLE 450 VOLT TRANSFORMERS

by
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United States Naval Postgraduate School

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Chairman
Department of Electrical
Engineering.

Approved: [redacted]
Academic Dean

PREFACE

This comparison was made because of the BUREAU OF SHIP'S interest in 400 cycle 1000 volts for naval ships. The transformer in particular was chosen because of its simplicity of design, its inherent freedom from mechanical design considerations such as would be encountered in the design of rotating machinery, and the fact that since transformer action is a basic part of a majority of the electrical power machinery found aboard ship, much can be learned from a detailed study of transformers.

The authors are indebted to Professor C.V.O. Terwilliger of the Naval Postgraduate School, Annapolis, Md., for his guidance and assistance and to Mr. G.H. Cole, Associate Director, Research Laboratories, of the American Rolling Mill Company for detailed information concerning ARMCO Irons for transformer use.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SYMBOLS

B	Flux density in lines per square inch
D	Leg width in inches of transformer core
I_e	Eddy Current
I_{FL}	Full load current
I_h	Hysteresis current
I_{mag}	Magnetizing Current
I_o	Exciting Current
N	Number of turns required per coil
η	Efficiency Percent
W_o	Estimated thickness of outer coil in inches
W_i	Estimated thickness of inner coil in inches
K	Lamination stacking factor
E	R.M.S. Voltage per coil
P_T	Total losses in watts at full load
P_I	core losses, watts per cubic inch
R_T	Total copper resistance per coil
V	Volume of iron cubic inches

INTRODUCTION

In order to get a good comparison between 60 cycle 450 volt and 400 cycle 1000 volt transformers, it was decided to design both types along the simplest possible lines, and to stabilize those factors which would detract from a good comparison of:

1. Weight Copper
2. Weight Iron
3. Total Weight
4. Exciting Current
5. Efficiency

Both transformers were designed along the following lines:

1. 10 Kilowatt Capacity
2. One to one voltage ratio
3. Power Factor = 1
4. Core Laminations ".014 "Tran-Cor XXX".
5. Standard cotton insulation (".005)
6. Standard Core Shape (See Illustration No. 1)
7. Half of each winding on each leg, windings in series.
8. Both types of transformers designed for maximum efficiency at full load, i.e. Copper losses = core losses

The principle variable is the core flux density. Both 60 cycle and 400 cycle transformers were designed for highest efficiency for each of many flux densities, and plots

made of weights, exciting current as percent of Full load current, and efficiency, against the various design flux densities.

The 10 kilowatt capacity was chosen to insure large enough designs to keep relative insulation weights and volumes small and yet not so large that cooling ducts might be required.

ARMCO Tran-Cor XXX was used for cores of both types because of its extremely high electrical properties. This iron is available only in ".014 thickness. It was found that nothing was gained in using thinner laminations of high frequency Silicon steels in the 400 cycle designs as the smaller gage materials indicate higher losses at 400 cycles and also have a lower stacking factor in comparison to Tran-Cor XXX.

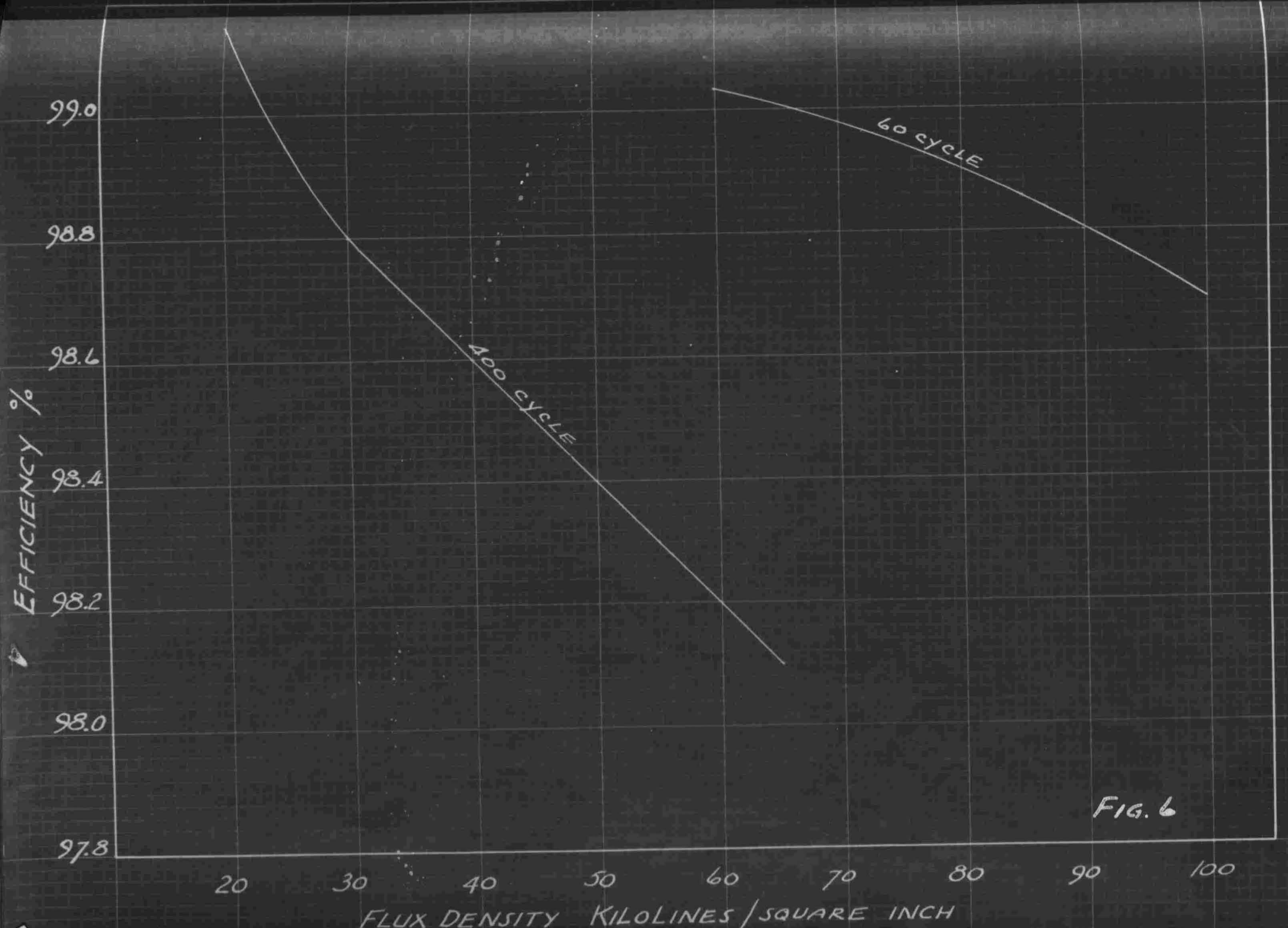
The results of this comparison are represented by Illustrations nos. 6,7 and 8. A comparison of individual designs can hardly be made as no "best" transformer can be chosen without knowing the application and desired characteristics.

Since weight saving is of prime importance in naval ships, somewhat of a comparison of the two types of transformers can be made by noting the characteristics of a 60 cycle transformer designed for a maximum flux density of 75,000 lines and that of a 400 cycle transformer designed at 30,000 lines, the designs above which the respective total weight curves increase slope rapidly.

	60 Cycles	400 Cycles
Total Weight	307 lb.	89 lb.
Exciting Current %	1.3%	0.67%
Efficiency	98.95%	98.80%

Note that the 400 cycle design weigh only 0.29 as much as the 60 cycle design. The small difference in efficiencies is not important in transformers for naval shipboard use. The 400 cycle exciting current as percent of full load current is reduced to 0.515 of that for the 60 cycle design.

The authors conclude that in so far as transformer action is concerned, going to 400 cycles and 1000 volts offers tremendous savings in weight and space. It is to be noted that there are many other factors to be considered before any definite conclusion can be reached concerning the overall effect of the higher frequency high voltage A.C. for ships.


99.0
98.8
98.6
98.4
98.2
98.0
97.8
EFFICIENCY %
60 CYCLE
400 CYCLE
20
30
40
50
60
70
80
90
100
FLUX DENSITY KILOLINES / SQUARE INCH
FIG. 6

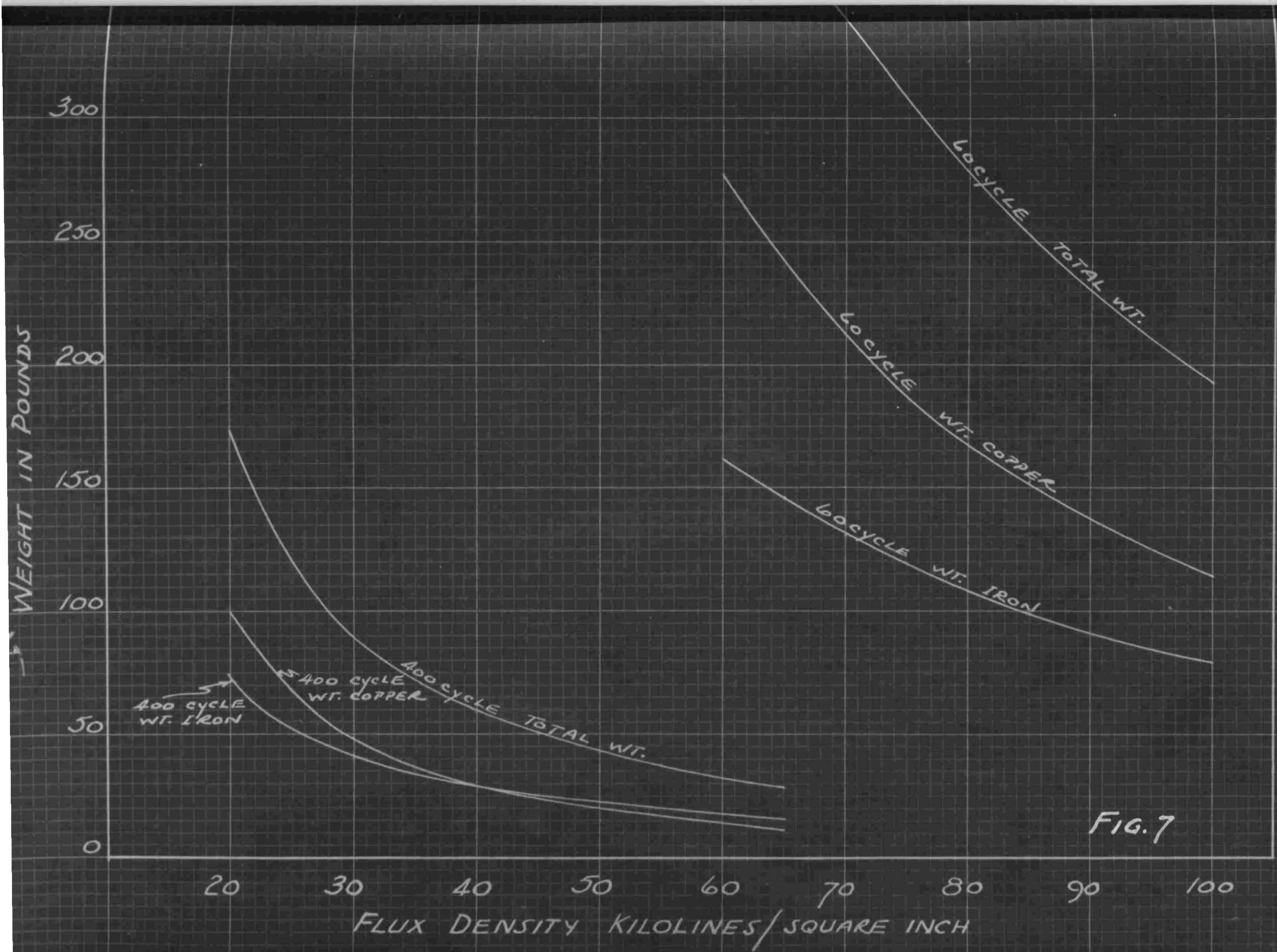

300
250
200
150
100
50
0
WEIGHT IN POUNDS
20
30
40
50
60
70
80
90
100
FLUX DENSITY KILOLINES/SQUARE INCH
60 CYCLE TOTAL WT.
60 CYCLE WT. COPPER
60 CYCLE WT. IRON
400 CYCLE TOTAL WT.
400 CYCLE WT. COPPER
400 CYCLE WT. IRON

FIG. 7

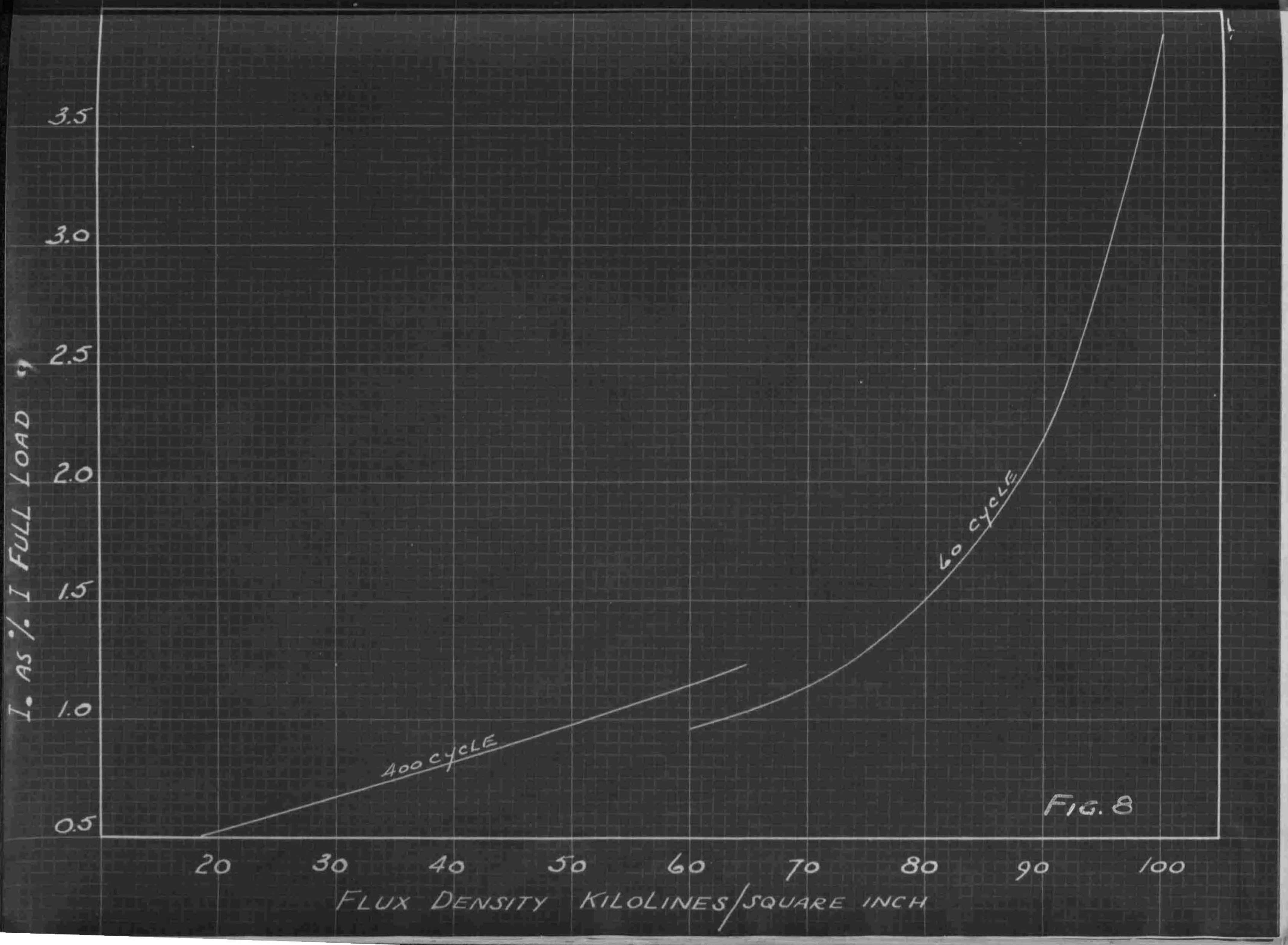

3.5
3.0
2.5
2.0
1.5
1.0
0.5
I. AS % I FULL LOAD
60 CYCLE
400 CYCLE
20
30
40
50
60
70
80
90
100
FLUX DENSITY KILOLINES/SQUARE INCH

FIG. 8

Basic Design Features (see fig. 1.)

1. Calculation of dimensions, efficiency, and weights.

$$P_t = (100 - \eta) \times K.V.A. \times 10$$

core losses $= \dfrac{P_T}{2} = 4I^2 R_T$

$$V = \frac{40\ KD^3}{3}$$

Then: $P_T/2 = \dfrac{40\ KD^3}{3} \times P_I$

and: $D = \sqrt[3]{\dfrac{P_T \times 3}{2P_I \times 40\ K}}$

$$E_{max} = N\frac{d\phi}{dt} \times 10^{-8} = 2\pi N f B D^2 K \times 10^{-8}$$

$$E = \sqrt{2}\,\pi N f B D^2 K \times 10^{-8} \doteq 4.44\ N f B D^2 K \times 10^{-8}$$

and: $N = \dfrac{E \times 10^8}{4.44 \times f B D^2 K}$

$$I_{FL} = \frac{K.V.A. \times 1000}{E}$$

$$R_T = \frac{P_T}{8 \times (I_{FL})^2}$$

All clearances between coils, and between coils and core including end clearances, are 0.25 inches. The window dimensions are 4D/3 and 10D/3. The total window area available for the winding on one leg is then;

$$\left(\frac{10D}{3} - 0.5\right)\left(\frac{4D}{3} - 1.25\right)\frac{1}{2}$$

The resistance of copper at 60 degrees centigrade is 12 ohms per circular mil foot. Using this value, the length and rectangular dimensions of the conductors were calculated. Double cotton insulation of 0.005 inches thickness was incorporated in the calculation of the total coil cross-sectional area. For each design flux density, efficiency was varied until the final dimensions were satisfied. From this point, the mass of iron and copper were readily computed.

2. Calculation of No Load Current.

$$I_{e+h} = P_T/2E$$

$$I_{mag} = \frac{4 \times NI/\text{Lap Joint} + (\text{Length Flux Path}) + NI/\text{inch}}{2N}$$

Then : $$I_0 = \sqrt{(I_{e+h})^2 + (I_{mag})^2}$$

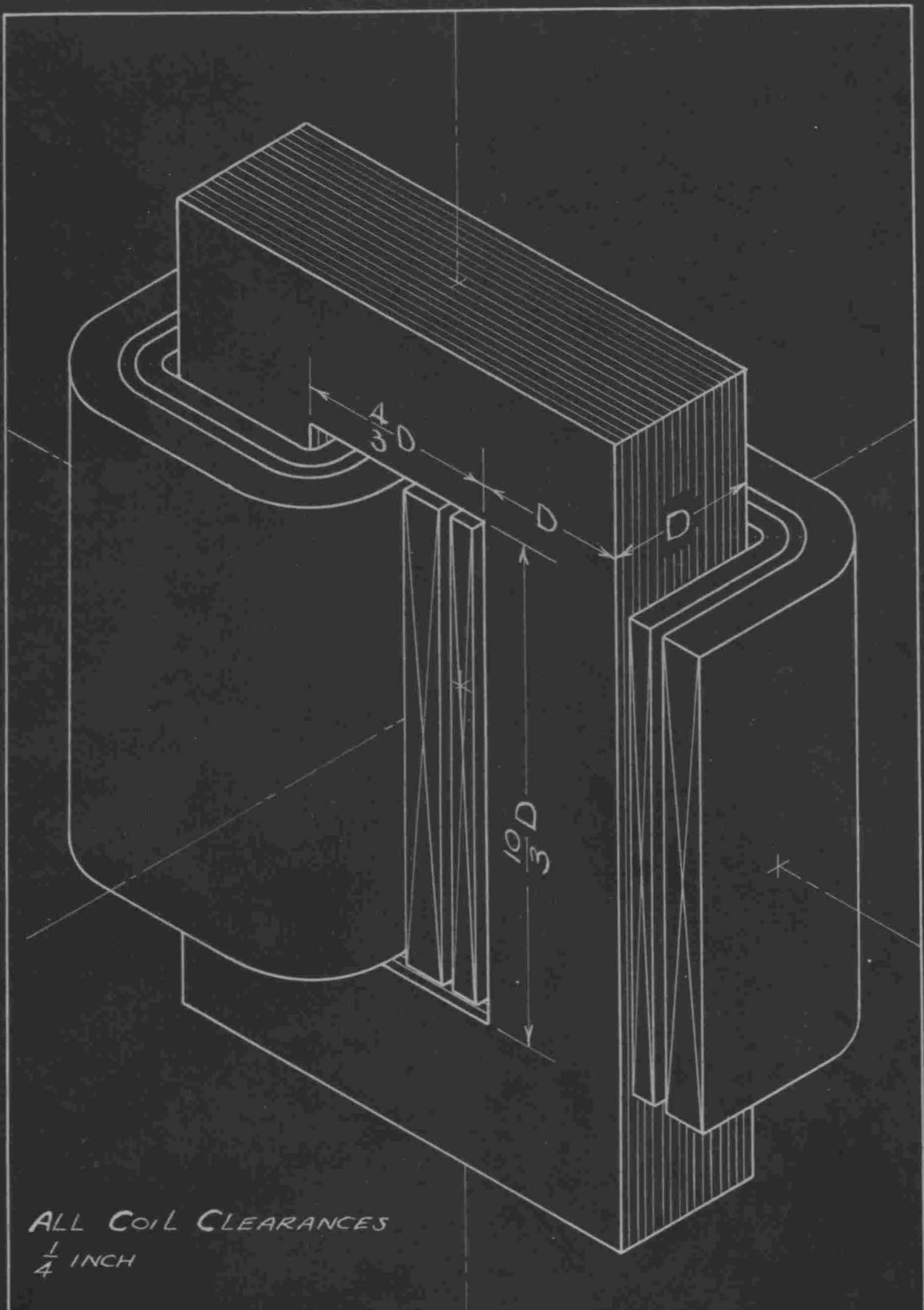


FIG. 1

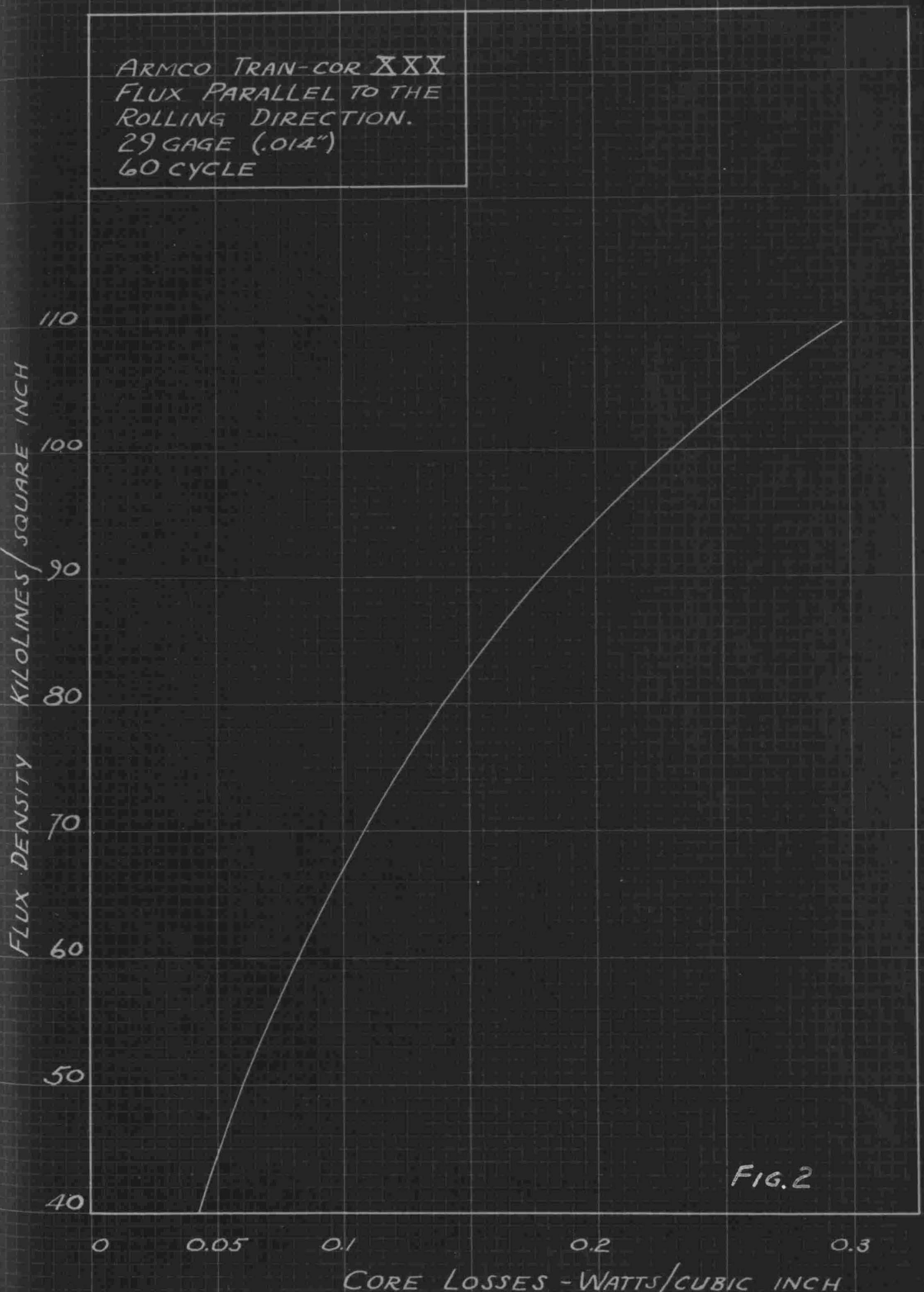
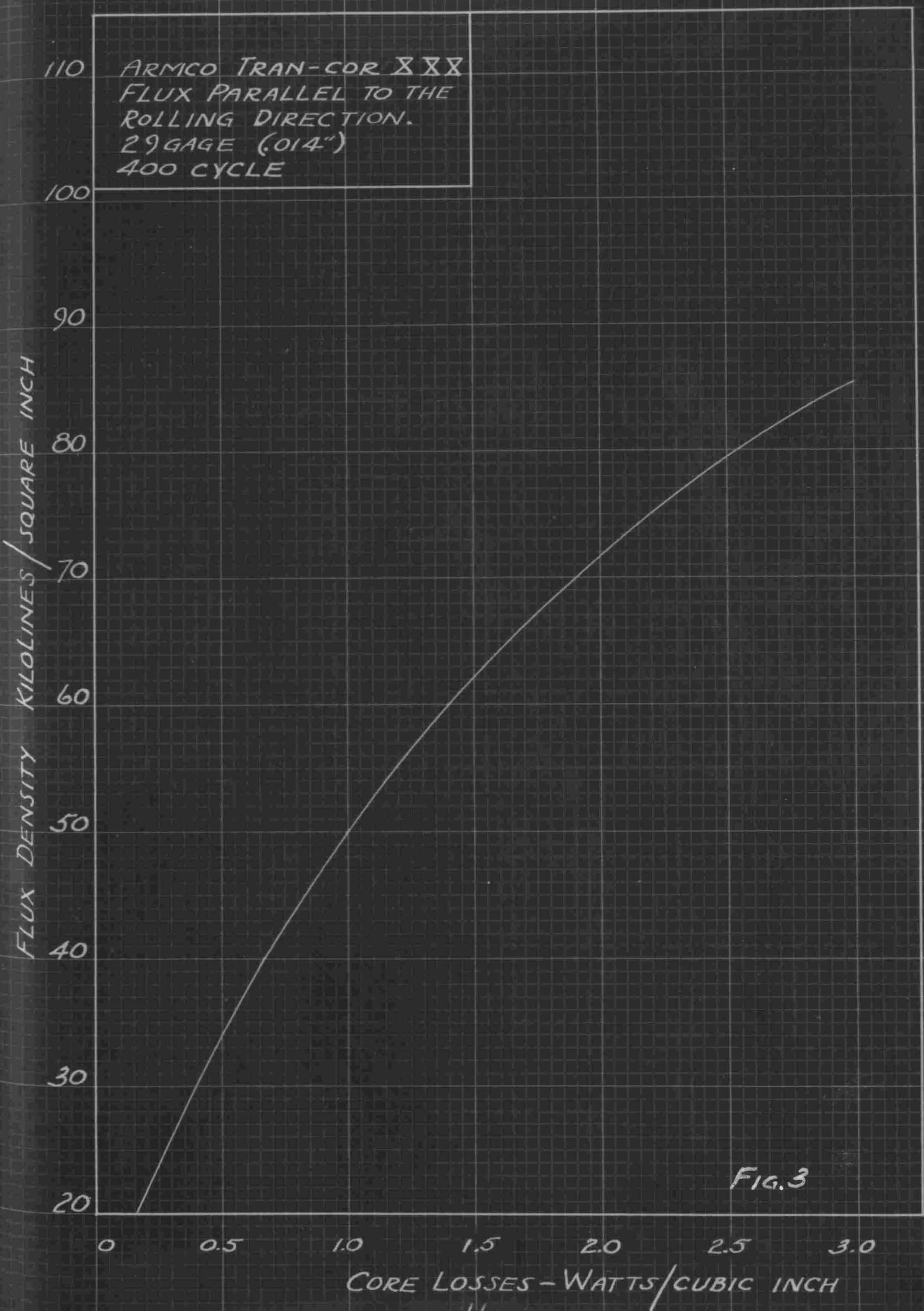
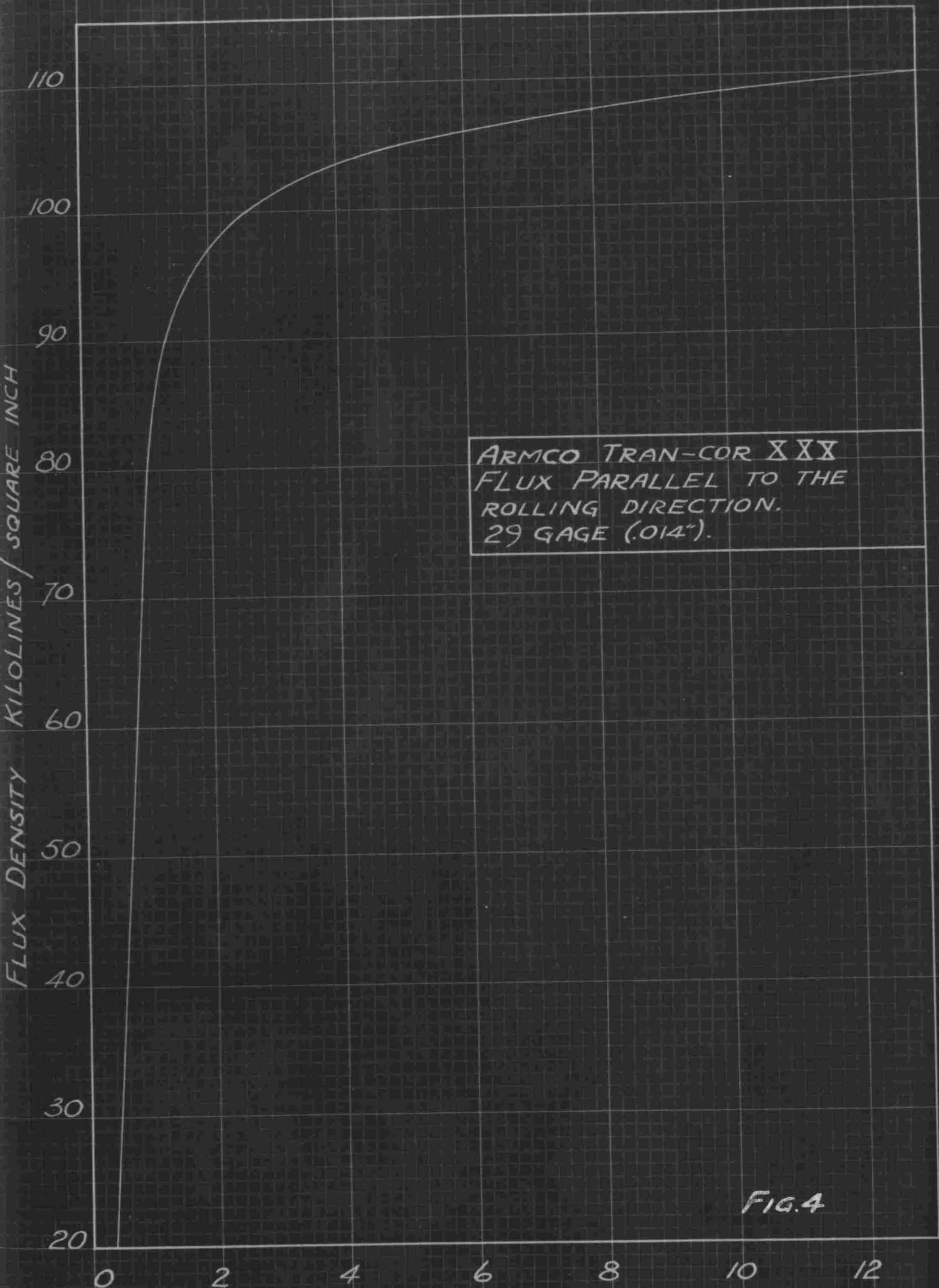
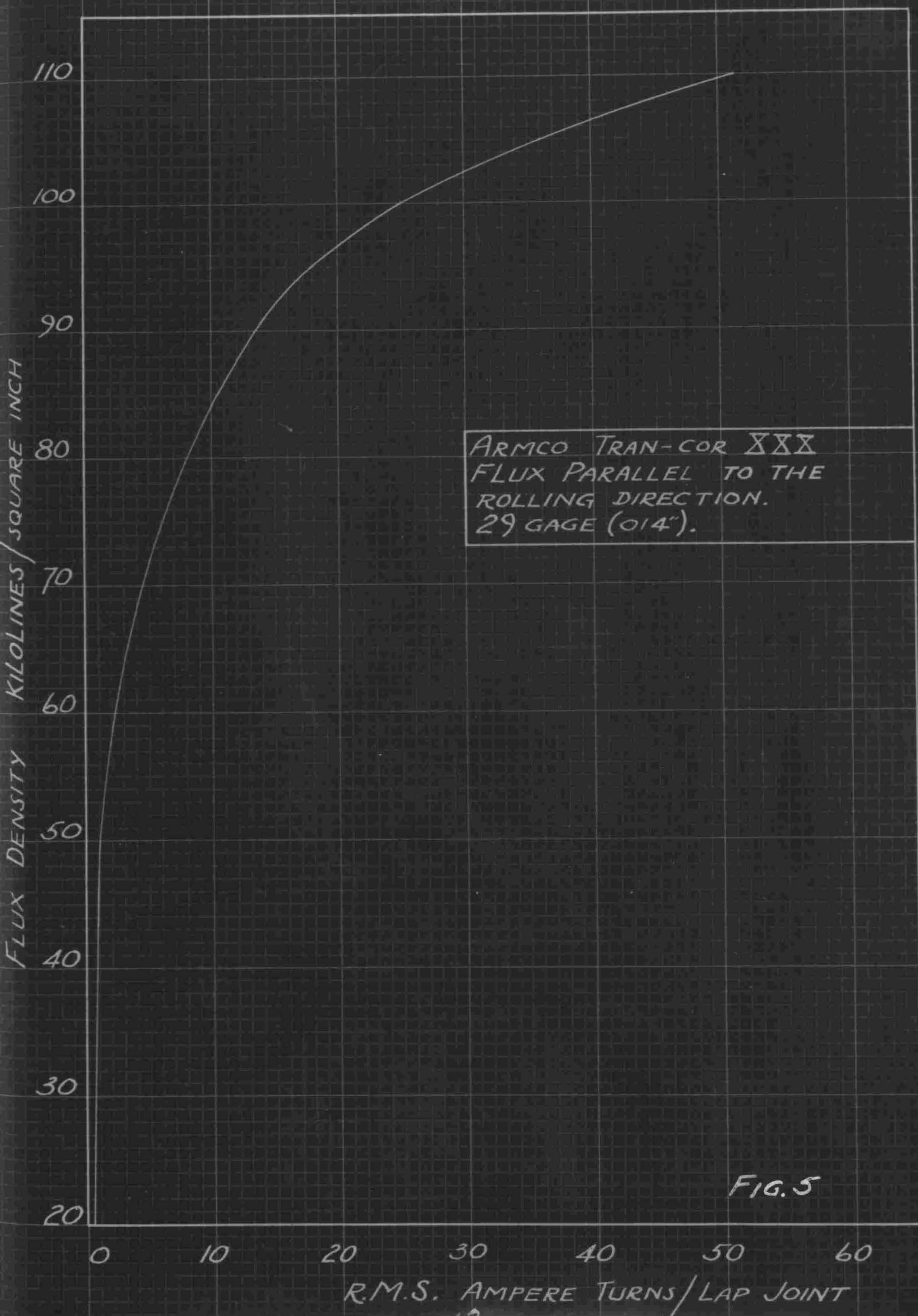

ARMCO TRAN-COR XXX
FLUX PARALLEL TO THE
ROLLING DIRECTION.
29 GAGE (.014")
60 CYCLE
FLUX DENSITY KILOLINES / SQUARE INCH
40
50
60
70
80
90
100
110
0
0.05
0.1
0.2
0.3
CORE LOSSES - WATTS/CUBIC INCH

FIG. 2


ARMCO TRAN-COR XXX
FLUX PARALLEL TO THE
ROLLING DIRECTION.
29 GAGE (.014")
400 CYCLE
110
100
90
80
70
60
50
40
30
20
FLUX DENSITY KILOLINES / SQUARE INCH
0
0.5
1.0
1.5
2.0
2.5
3.0
CORE LOSSES - WATTS/CUBIC INCH
FIG. 3



ARMCO TRAN-COR XXX
FLUX PARALLEL TO THE
ROLLING DIRECTION.
29 GAGE (.014").
FIG. 4
FLUX DENSITY KILOLINES / SQUARE INCH
110
100
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
R.M.S. AMPERE TURNS/INCH



110
100
90
80
70
60
50
40
30
20
FLUX DENSITY KILOLINES/SQUARE INCH
ARMCO TRAN-COR XXX
FLUX PARALLEL TO THE
ROLLING DIRECTION.
29 GAGE (.014").
0
10
20
30
40
50
60
R.M.S. AMPERE TURNS/LAP JOINT

FIG. 5

60 CYCLE CALCULATIONS

1.	Design Flux Density B	60,000	65,000	70,000
2.	Efficiency η	99.033	99.024	98.972
3.	Watts loss /2	48.5	48.8	51.35
4.	Watts /in^3 Iron	.083	.0926	.1088
5.	Volume Iron #3 /#4	585	527	472
6.	#5 /12.8 D^3	45.6	41.2	36.85
7.	$\sqrt[3]{\#6}$ D	3.553	3.45	3.322
8.	Half Window 0.667 D	2.37	2.304	2.218
9.	Height Window 10/3 D	11.82	11.52	11.08
10.	Turns /Coil $88 \times 10^6 / BD^2$ N	114.7	113.8	113.4
11.	Estimated Outer Coil Space W_o	1.034	.706	.920
12.	EStimated Inner Coil Space W_i	.738	.973	.673
13.	Length mean turn inner Coil $4D + 6.28(.25 + W_i/2)$	18.1	17.60	16.96
14.	Watts loss /Coil #3/4	12.125	12.2	12.83
15.	Cross Section Inner Coil $38.75 \times 10^{-5} \times$ #13 x #10 /#14	.0661	.0629	.0583
16.	Turns /layers inner Coil	39/3	38/3	38/3
17.	Vert. cu. /turn inner Coil	.2804	.2802	.2685
18.	Horiz. cu. /turn inner Coil	.236	.2244	.217
19.	Width inner Coil	.738	.703	.682
20.	Space left for outer Coil	1.007	.976	.911
21.	Length mean turn outer Coil 4D+6.28 (.5 + #19 + #20 /2)	25.1	24.43	23.56
22.	Cross section outer Coil $38.75 \times 10^{-5} \times$ #21 x #10 /#14	.092	.0885	.0810
23.	Turns /layers outer Coil	39/3	38/3	38/3
24.	Vert. cu. /turn outer Coil	.2804	.2802	.2685
25.	Horiz. cu. /turn outer Coil	.3278	.3157	.3017
26.	Width Outer Coil	1.0134	.977	.936
27.	Weight Iron 0.2763 x #5	161.7	145.8	130.8
28.	Weight Copper, #10 x 0.644 x (#13 x #15 + #21 x #22)	277.5	240.5	212.5
29.	Length mean flux path 4 x #8 + 2 x #9 + 3.1416D	44.29	43.09	41.48
30.	Ampere-Turns /inch	.71	.82	.87
31.	Ampere-Turns /Lap Joint	2.5	3.0	4.0
32.	Total Ampere Turns #29 x #30 + 4 x #31	43.22	47.3	52.1
33.	I_{mag} #32 /2 x #10	.1889	.2075	.228
34.	I_{eth} #3 /450	.1079	.1084	.1142
35.	$I_o = \sqrt{(I_{mag})^2 + (I_{eth})^2}$	.2175	.234	.255
36.	I_o as $\%I_{FL}$ #35 /0.2225	.979	1.05	1.15

80,000	85,000	90,000	95,000	100,000
98,902	98,858	98,805	98.75	98.689
54.9	57.1	59.75	62.5	65.55
.1402	.1583	.1795	.203	.229
392	360.7	332.5	307.5	285.8
30.6	28.2	26.0	24.02	22.34
3.125	3.041	2.961	2.884	2.817
2.086	2.029	1.975	1.924	1.876
10.42	10.13	9.87	9.61	9.38
112.7	111.9	111.2	111.1	111.1
.841	.810	.78	.750	.722
.620	.594	.57	.549	.5295
16.03	15.61	15.2	14.85	14.51
13.73	14.27	14.94	15.625	16.39
.0502	.0471	.0438	.04095	.0382
37/3	37/3	37/3	37/3	37/3
.2582	.2505	.2435	.2362	.230
.1943	.1879	.180	.1732	.1661
.613	.593	.57	.5496	.5283
.847	.811	.78	.7494	.723
22.15	21.58	21.00	20.45	20.00
.0693	.0651	.06055	.05655	.0526
37/3	37/3	37/3	37/3	37/3
.2582	.2505	.2435	.2362	.230
.2682	.2597	.2491	.2395	.229
.834	.809	.7773	.7485	.717
108.3	99.8	91.9	85.1	78.8
167.7	152.8	145.6	126.0	114.3
39.01	37.93	36.95	35.994	35.114
1.04	1.15	1.3	1.68	2.55
8.0	10.6	13.5	17.8	24.9
72.6	86.0	102.0	131.6	189.2
.327	.388	.4575	.591	.85
.1222	.1269	.133	.139	.1459
.349	.408	.476	.606	.863
1.57	1.84	2.15	2.73	3.89

400 CYCLE CALCULATIONS

1.	Design Flux Density	B	20,000	25,000	30,000
2.	Efficiency	η	99.15	98.947	98.8
3.	Watts loss /2		42.5	52.5	60
4.	Watts /in³. Iron		.16	.275	.4
5.	Volume Iron #3 /#4		265.5	191.0	149.8
6.	#5/12.8	D^3	20.76	14.92	11.7
7.	$\sqrt[3]{\#6}$	D	2.747	2.461	2.272
8.	Half Window	.667 D	1.833	1.642	1.515
9.	Height Window	10/3 D	9.16	8.21	7.56
10.	Turns /Coil $29.30\times10^6/BD^2$	N	193.2	193.6	189
11.	Estimated Outer Coil Space	W_o	.689	.583	.514
12.	Estimated Inner Coil Space	W_i	.5195	.434	.3761
13.	Length mean turn inner coil 4D + 6.28(.25 + W_i /2)		14.2	12.78	11.81
14.	Watts loss /coil #3/4		10.625	13.12	15.00
15.	Cross section inner coil 7.85×10^{-5} x #13 x #10 /#14		.02027	.01496	.01172
16.	Turns /layers inner coil		65/3	65/3	63/3
17.	Vert. cu. /turn inner coil		.1234	.1087	.1022
18.	Horiz. cu. /turn inner coil		.1642	11378	.1148
19.	Width inner coil		.5226	.443	.3744
20.	Space left for outer coil		.6849	.574	.5156
21.	Length mean turn outer coil 4D + 6.28(.5 + #19 + #20 /2)		19.5	17.57	16.18
22.	Cross section outer coil 7.85×10^{-5} x #21 x #10 /#14		.0271	.0202	.01604
23.	Turns/layers outer coil		49/4	65/3	63/3
24.	Vert. cu. /turn outer coil		.167	.1087	.1022
25.	Horiz. cu./turn outer coil		.1622	.1883	.1568
26.	Width outer coil		.6888	.594	.5004
27.	Weight Iron 0.2763 x #5		73.4	52.1	41.4
28.	Weight Copper #10 x 0.644(#13x#15 + #21 x #22)		101.2	68.3	48.4
29.	Length mean flux path 4 x #8 + 2 x #9 + 3.1416D		34.29	30.72	28.31
30.	Ampere-Turns / inch		.245	.40	.45
31.	Ampere-Turns /Lap Joint		.5	.6	.75
32.	Total Ampere Turns #29 x #30 + 4 x #31		10.4	14.7	15.71
33.	I_{mag} #32 /2 x #10		.0269	.0377	.0415
34.	I_{eth} $\frac{\#3}{1000}$		.0425	.0525	.06
35.	$I_o = \sqrt{(I_{mag})^2 + (I_{eth})^2}$		.0504	.0646	.073
36.	I_o as $\%I_{FL}$ #35 x 10		.504	.646	.730

35,000	40,000	45,000	50,000	55,000	60,000	65,000
98.70	98.60	98.50	98.42	98.30	98.2	98.10
65	70	75	79	85	90	95
.525	.67	.820	.99	1.19	1.41	1.64
123.8	104.2	91.4	79.6	71.4	63.8	57.9
9.67	8.15	7.14	6.23	5.58	4.99	4.52
2.13	2.01	1.922	1.843	1.772	1.709	1.653
1.421	1.34	1.283	1.23	1.182	1.1395	1.103
7.10	6.7	6.41	6.145	5.91	5.699	5.515
184.8	181.7	176.2	172.3	169.8	167.9	165.2
.458	.413	.378	.346	.319	.288	.274
.338	.302	.280	.2592	.238	.221	.204
11.15	10.53	10.13	9.75	9.40	9.09	8.83
16.25	17.5	18.77	19.75	21.25	22.5	23.75
.01002	.00861	.00752	.00669	.00593	.00533	.00482
62/3	61/3	59/3	58/3	57/3	56/3	55/3
.0964	.0918	.0902	.0873	.0848	.0828	.0812
.1040	.0939	.0834	.0766	.0700	.0644	.0593
.342	.3117	.280	.2598	.240	.2232	.208
.454	.4033	.378	.3452	.317	.2913	.270
15.24	14.4	13.76	13.21	12.73	12.25	11.91
.0137	.01177	.01020	.00909	.00805	.00719	.00651
62/3	61/3	59/3	58/3	57/3	56/3	55/3
.0964	.0198	.0902	.0873	.0848	.0828	.0812
.1422	.1281	.1131	.1041	.0949	.0864	.0801
.456	.4143	.369	.3423	.315	.2892	.270
34.3	28.8	25.2	22.0	19.8	17.62	16.0
38.4	30.3	24.7	20.55	17.4	14.7	12.8
26.56	25.06	24.00	23.00	22.12	21.32	20.64
.50	.57	.60	.67	.70	.77	.82
.80	.9	1.0	1.0	1.4	2.2	3.0
16.5	17.9	18.4	19.42	21.1	25.21	28.9
.0444	.0492	.0518	.0563	.0616	.075	.0875
.065	.07	.075	.079	.085	.09	.095
.0786	.0856	.0912	.097	.105	.117	.1252
.786	.856	.912	.97	1.05	1.17	1.252

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